Institution: Liverpool John Moores University (LJMU)		
Unit of Assessment: UOA7 Earth Systems and Environmental Sciences		
Title of case study: Building the capacity of environmental managers to mitigate mine pollution		
Period when the underpinning research was undertaken: 2014 - 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Patrick Byrne	Senior Lecturer in Geography	2012 (Sept) to present
Period when the claimed impact occurred: August 2014 to March 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Mine wastes are identified by the UN Environment Programme and the UK Governments 25 Year Environment Plan as major barriers to environmental and socio-economic improvement in the 21st century. With limited resources, and exacerbation of mine pollution by climate change, the major challenge facing governments and environmental managers is how to prioritise mine sites for remediation that will deliver the most benefit to the environment and communities. The research led by Byrne, and conducted in the UK and USA, led to national and international impact on practitioners and improvements to the water environment. Application of novel monitoring and modelling approaches, in conjunction with training workshops, has: [1] changed how environmental regulators monitor mine pollution; [2] secured mine site remediation funding awards worth GBP£1.8M, and; [3] reduced pollution of water bodies by mine wastes.

2. Underpinning research

Previous research led by Byrne utilised a carefully designed synoptic sampling approach, using synchronous measures of streamflow and metal concentrations, to identify secondary sources of pollution following a major mine waste spill in Canada in 2014 (**RG1, O1**). However, this widely used method is labour intensive, costly, and time consuming, and does not provide the necessary spatial detail to locate and quantify important diffuse sources of mine pollution such as groundwater, potentially limiting the efficacy of remediation interventions. Building on this experience, the work led by Byrne, from August 2014 to March 2020, has utilised a novel tracer dilution and synoptic sampling approach in UK and USA watersheds to vastly improve detection and modelling of mine pollution sources, in particular diffuse groundwater sources, whilst reducing financial and labour costs (**RG2, RG3**).

Identifying diffuse groundwater sources of pollution in mining-impacted watersheds:

A key achievement has been to improve the spatial resolution and accuracy of mine pollution detection by using a tracer dilution approach. Diffuse sources of mine water pollution such as groundwater are difficult to locate and quantify accurately using traditional sampling protocols, due to their lower spatial coverage and greater error in streamflow estimates. Work by Byrne in the UK (Afon Ystwyth, Crawick Water) and USA (Clear Creek) quantified the substantial importance of (mining) polluted groundwater to overall watershed water quality (**O2, O3, O4, O5, O6**). In the Afon Ystwyth headwaters, the contribution of groundwater to total stream water increased from 25% during mean streamflow to 66% under low stream flow conditions (**O6**). This is a highly significant finding for two reasons: (i) low stream flows are predicted to become more common and severe as a consequence of climate change; (ii) the difficulty of identifying polluted groundwater sources means they are generally not considered in watershed remediation programmes.

Establishing metal sources and flux under varying hydrological conditions:

A major limitation of mine pollution detection methods has been application under variable streamflow conditions which are known to change the location and importance of mine pollution sources. Addressing this challenge, we developed a multi-tracer approach that combines high spatial resolution surveys of mine pollution sources under steady-state flow conditions, with lower spatial resolution surveys of key identified sources under variable flow conditions. Utilising this approach in the Afon Ystwyth, we have been able to track variability in mine pollution sources across several years with previously unattainable spatial and temporal resolution (**O3, O6**). Significantly, we found that during times of extreme low flows, stream water chemistry becomes dominated by mine pollution from groundwater. Furthermore, saturation of certain minerals alters the transport dynamics of metal pollutants at low flow, leading to greater contamination and ecotoxicity in the vicinity of mine sites. Considering low flows are predicted to increase in frequency and magnitude due to climate change, these hydrological and geochemical changes could have substantial negative consequences for biodiversity and ecosystem service provision in upland environments.

Modelling hypothetical remediation scenarios in watersheds impacted by mining:

A major advantage of the tracer dilution and synoptic sampling approach is the generation of high quality and observed water chemistry and streamflow data. We used these data to calibrate solute transport models for the headwaters of the Afon Ystwyth (Wales) and the Crawick Water (Scotland) and simulated how different proposed remediation scenarios might affect water quality (**O5, O6**). This represents a step-change in how potential water quality improvements from remediation are evaluated. Specifically, our research demonstrated how remediation of surface mine waste sources may not improve water quality as expected due to the control of polluted groundwater on stream water quality.

3. References to the research

All outputs have been through a rigorous peer-review process (Note: key publications are O2, O5 and O6):

[O1] Byrne P, Hudson-Edwards KA, Bird G, Macklin MG, Brewer PA, Williams RD, Jamieson HE. (2018). Water quality impacts and river system recovery following the 2014 Mount Polley mine tailings dam spill, British Columbia, Canada, *Applied Geochemistry*, 91: 64-74. DOI

[O2] Byrne P, Runkel RL, Walton-Day KA. (2017). Synoptic sampling and principal components analysis to identify sources of water and metals to an acid mine drainage stream, *Environmental Science and Pollution Research*, 20: 17220-17240. DOI *(Establishes the importance of groundwater pollution in mining-impacted river systems)*

[O3] Onnis P, Byrne P, Hudson-Edwards KA, Stott T, Hunt C. (2018). Source apportionment of trace metals over a range of stream flows using a multi-method tracer approach. 11th ICARD-IMWA-MWD Conference – Risk to Opportunity, 1: 843-843. URL *(Develops a novel multi-tracer approach for detection of mine pollution sources at high spatial resolution across streamflows)*

[O4] Runkel RL, Verplanck PL, McCleskey RB, Walton-Day K, Byrne P. (2019). Synoptic sampling data from Illinois Gulch and Iron Springs near Breckenridge, Colorado, August 2016 and September 2017, U.S. Geological Survey Data Release. DOI

[O5] Byrne P, Yendell A. (2020) Source apportionment of metal mine pollution in Wanlock Water using tracer injection and synoptic sampling, *Scottish Environment Protection Agency*. URL *(Novel method application allowed prioritisation of mine pollution sources and remediation scenario modelling)*

[O6] Byrne P, Onnis P, Runkel RL, Frau I, Lynch SFL, Edwards P. (2020) Critical shifts in metal transport and remediation effectiveness under future low river flows, *Environmental Science and Technology*, DOI *(Established, for the first time, how climate change may modify water quality, metal transport processes, and remediation effectiveness under extreme low flows)*

Key research grants:

[RG1] 2014 – 2015, NERC, The long-term environmental impacts of the Mount Polley mine tailings spill and related clean-up operations, British Columbia, Canada, £64,950.
[RG2] 2018 – 2019, NERC, Developing environmental regulator capability in source apportionment and remediation of mine pollution, £37,034.
[RG3] 2019 – 2020, SEPA, Source apportionment of metal mine pollution in the Leadhills area using novel fieldwork techniques, £17,000.

4. Details of the impact

Research and training exercises developing and applying novel approaches for the monitoring and remediation of pollution in mining-impacted watersheds has had substantial impacts on environmental manager practice at national and international scales. Examples of the impacts within the period 2014 (August) to 2020 (March), all with documentary evidence, include:

(A) National impact on regulators and the water environment:

The impacts described here arose from applying research findings **[O3]**, **[O5]** and **[O6]**. Byrne's work in the Afon Ystwyth (Wales) demonstrated that 20% of the mine pollution in the headwaters originated from Graig Goch Mine. Knowledge of this previously undocumented source of pollution changed Natural Resources Wales' (NRW) approach to remediation in this watershed. Commenting on the specific data that led to this change, the Lead Specialist Engineer (Geotechnical) stated:

"Without the work of Dr Byrne we may have committed up to £3M on remedial work without understanding the resulting loading from Graig Goch that would cause the waterbody to fail to attain WFD Good status." **[S1]**

Utilising LJMUs research and data to inform a new remediation plan, NRW applied for and secured GBP£1.78M from the Welsh Government to remediate the identified sources of pollution in the Afon Ystwyth. The NRW Sustainable Land Manger commented:

"The LJMU studies in the Nant Cwmnewyddion stream have directly informed the prioritisation and design of remedial measures at Frongoch and Wemyss mines, for which NRW has allocated £1.78M in 2020/21" **[S2]**

On the general research collaboration between LJMU (Byrne) and NRW, the NRW Sustainable Land Manger commented:

"This partnership has produced research that has directly informed our Metal Mines Remediation programme" by providing *"an improved evidence base for mine site remediation"* and by *"improving scientific understanding and changing monitoring practice"* **[S2]**

On the LJMU collaboration with the Scottish Environment Protection Agency (SEPA), a Contaminated Land Specialist stated the research helped SEPA to:

"make better decisions moving forward with actions to reduce the impact of historic mining" **[S3]**

These are clear statements of the impact of Byrne's research from 2014 to 2020, in influencing government (regulator) practice and investment in environmental problems and solutions. Furthermore, the partnership between LJMU and NRW was cited in NRWs' entry to the Wales Science, Technology, Engineering and Mathematics (STEM) Awards 2020 **[S1]**, for which NRW has been shortlisted for the categories "STEM Environmental Initiative of the Year" and "STEM Company of the Year (250+ employees)".

(B) International impact on practitioners and the water environment:

Since 2014, Byrne has worked in partnership with U.S. environmental managers and the U.S. Geological Survey to conduct research that directly informs and shapes remediation practice in mining-impacted watersheds in the U.S.A. The impacts arose from applying research findings **[O2]** and **[O4]**.

Utilising the research undertaken by Byrne in the Clear Creek watershed, the Abandoned Mine Restoration Project Manager for Trout Unlimited stated:

"…Trout Unlimited were able to secure funding (USD$28,673) for, and install, surface water diversion structures at Minnesota Mine shaft in the fall of 2018" **[S4]**

These diversion structures were crucial for reducing surface water inflow into the Minnesota Mine, and subsequently reducing mine-impacted water entering Clear Creek, a major fishery, recreation area, and drinking water source to the Denver Metropolitan Area. The infrastructure installed as a consequence of Byrne's research led to a quantifiable change in the water environment:

"Continued monitoring of the diversion structures in 2019 proved their effectiveness at reducing inflow into the Minnesota Mine and, thus, reducing the volume of mine-impacted waters entering Lion Creek and downstream water resources" **[S4]**

On the general impact of Byrne's research on mine site remediation planning in Colorado, key collaborating stakeholders stated that:

"Our work together has proved essential to developing science-based, effective mine site remediation plans that improve environmental conditions and protect human health." **[S4]**

"This partnership has produced research that directly informed U.S. Forest Service about the type of remediation needed on National Forest Service lands." **[S5]**

This is clear evidence of the impact of Byrne's research on mine site remediation decision-making and water environmental improvement internationally.

(C) National impact on monitoring practice:

Byrne's research has changed the monitoring practices of environmental regulators in the UK through a programme of knowledge exchange based around classroom and field training activities (2018 (March) to 2020 (March)). These activities have been attended by 35 people from across the environmental sector, including environmental regulators, Universities and environmental consultancies. The work is underpinned by a NERC Innovation Placement Award to Byrne **[RG2]**.

Commenting on the transformative nature of the LJMU-NRW collaboration, a senior NRW engineer [S1] and manager [S2] said:

"The work led by Dr Byrne has been that successful at identifying the significance of hyporheic (groundwater) loading that NRW wishes to extend this to other sites in our Programme where remedial treatment systems are being considered to combat abandoned metal mine discharges." **[S1]**

"NRW has changed its approach to investigating pollution from abandoned metal mines and interpreting the data obtained from previous investigations since collaborating with LJMU" **[S2]**

"Tracer-dilution is now our preferred method of flow gauging at mine-impacted sites and the data obtained from this monitoring will be used to refine our existing watershed models or to develop new models" **[S2]**

These statements provide clear evidence of how the research and training conducted by Byrne has changed the way environmental regulators in the UK detect and monitor pollution in mining-impacted watersheds.

5. Sources to corroborate the impact

[S1] Testimonial from Lead Specialist Engineer (Geotechnical), Natural Resources Wales

[S2] Testimonial from Sustainable Land Manager, Natural Resources Wales

[S3] Testimonial from Contaminated Land Officer, Scottish Environment Protection Agency

[S4] Testimonial from the Abandoned Mine Restoration Project Manager, Trout Unlimited, (Colorado, USA)

[S5] Testimonial from the Forest Abandoned Mine Lands Program Manager, U.S. Forest Service (Colorado, USA)